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THE EFFECT OF ADDING MAGNESIUM TO THE FILLER MATERIAL ON THE HARDNESS OF TIG WELDED ALUMINIUM ALLOY-AA 6082

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ABSTRACT

Aluminium 6082 is one of the most extensively used alloys in the industry due to its good mechanical properties and weldability. TIG welding is a most common joining process for this alloy as it results in better quality weld compared to other methods of welding. Aluminium 6082 is mainly used in automotive, shipbuilding, aircraft and structural applications. Deterioration of the mechanical properties of the weld metal and weakening of the heat-affected zone compared to the parent metal are the main issues in the welding of aluminium alloys. By carefully selecting proper welding parameters and by using proper filler materials these issues can be minimized to a certain extent. Chemical composition of the filler material has a significant effect on the mechanical properties of the welded joint. ER 4043, which contains 5% silicon as major alloying element and ER5356, which contains 5% magnesium as major alloying element, are the most common filler materials used for the welding of AA6082 alloys. In the present investigation, the chemical composition of the filler wire is altered by adding magnesium at different percentage levels to the commercially available ER 4043 filler wire. This new filler wire developed with altered chemical composition is used for the TIG welding of 6082 aluminium alloy. The effect of adding magnesium to the filler wire is investigated by using factorial design of experiments and analysis of variance. From the experiments, it is found that this new filler wire is capable of providing better hardness to the welded joint. It is also found that the increase in the hardness is due to the formation of magnesium silicide intermetallic compound in the weld metal. From the microstructural analysis by using SEM, the presence of various intermetallic phases is identified. The amount of magnesium to be added in the filler for obtaining the maximum hardness for the weld metal is optimized by using Factorial design, Artificial Neural Network and Genetic Algorithm.

KEYWORDS: Aluminium 6082, TIG Welding, Filler Wire, Mechanical Properties, Hardness of Weld Metal, Microstructure, Intermetallic Phase, Magnesium Silicide, Factorial Design, Artificial Neural Network & Genetic Algorithm

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Original Article

INTRODUCTION

Aluminium is one of the most commonly-used materials in industrial applications due to its excellent corrosion resistance, moderate strength, light weight and good machinability. It is extensively used in the manufacturing of automobile parts, aircraft bodies, trucks, railway coaches, cars, marine vessels, bicycle frames, spacecraft parts, transport equipment, storage tanks, general metal sheet works etc. [1]. To improve the mechanical properties, aluminium is commonly mixed with other metals like copper, manganese, silicon, magnesium and zinc to form different alloys. The aluminum alloys of 6000 series are extensively-used aluminium alloys for industrial applications due to their better mechanical properties.

Silicon and magnesium are the major elements added in the aluminium 6000 family series of alloys. High strength, excellent corrosion resistance, moderate weldabilty and good formability are the key properties of aluminium 6000 series of alloys [2-4]. AA 6061 and AA 6082 are the most preferred alloys in 6000 series, and these alloys are used in automotive, shipbuilding, aircraft and structural application [5]. The weldability of aluminium alloy is an important property that has significant role in its selection for specific applications.

Welding is a process used for making permanent joints between same metals or between two different types of metals or its alloys. Tungsten Inert Gas (TIG) welding is a process used for joining of metals by the heat produced from the arc established between the base metal and a non-consumable electrode [6-7]. It is one of the broadly used welding techniques in modern industries for joining either similar or dissimilar materials. The high melting point of tungsten is capable of withstanding the higher heat input used in TIG welding. Weld zone is protected by a shielding gas from atmospheric air and a filler material is normally used to deposit material in weld zone. Very good weld quality, low heat affected zone, absence of slag and capability for joining of similar and dissimilar metals are some of the advantages of TIG welding process. For welding of aluminum and its alloys, TIG welding method is generally used [5]. Welding of aluminum is a difficult process due to the presence of aluminium oxide layer on its surface. The melting point of aluminium oxide is very high compared to the melting point of aluminium. For achieving the quality of weld, it is very important to remove and disperse this oxide film before and during welding process [6-8]. This is achieved by applying very high heat input in the presence of inert shielding gas. Generally, argon, helium or a mixture of argon and helium is used as shielding gas to protect the molten metal from oxidation and atmospheric contamination. Filler metal is added externally to the arc in the form of a consumable wire. ER 4043, ER 4047, ER 5356 are some of the most common filler wires used for the TIG welding of 6000 series of aluminium alloys. The chemical composition of filler wire is a significant factor that influences the mechanical properties of the welded joint. In TIG welding process the arc act as a source of heat only and therefore a separate filler material is used to deposit material in the joint as weld pool. Selection of filler metal is very crucial for producing good quality welded joints with better mechanical properties. The selection of the filler material depends on mechanical properties, corrosion resistance, colour match, response to anodizing and creep strength required for the joint.

Shah et al. investigated the effect of a filler wire on the mechanical properties of AA6061 alloy welded by Tungsten Inert Gas (TIG). It is found that aluminium alloy welded with ER4043 filler wire showed improved Vickers hardness. Corrosion resistance of the joint also got improved compared to samples welded with ER4047 filler wire [9]. M. Ishaket. al. investigated the influence of filler on weld metal structure of TIG welded AA 6061 aluminum alloy. It is found that welding using ER5356 filler wire produced a finer grain size of 25.69 µm at the fusion zone. The average grain sizes obtained by ER4043 and ER4047 filler wires were 52.75 µm and 76.78 µm respectively. The filler wire ER5356 also produced highest hardness value of 72.9 HV compared to the hardness of weld metal obtained by either ER4043 or ER4047filler wires. The average value of hardness obtained by ER4043 and ER4047 filler wires were 59.3 HV and 57.6 HV respectively. The welded joints using ER5356 filler resulted in the highest value of tensile strength of 171.53 MPa compared to the tensile strength values of 167.34 MPa and 168.03 MPa obtained by using ER4043 and ER4047 filler wires. So, it was concluded that TIG welding using ER5356 filler yielded better joints compared to that produced by either ER4043 or ER4047 [10] . Ahmad WaelAlShaer et.al investigated the effect of filler on weld metal structure AC-170PX (AA6014). It was found that the filler wires with high Mg and Mn content such as AA5083 and AA3004 are capable of reducing porosity to a great extent. The porosity level obtained was nearly 1.5% for the joints made by both types of above filler wires compared with 80% porosity with the silicon-rich AA4043 wire [11]. S.R.Koteswara Rao et. al. investigated

the effect of scandium addition in the 2319 and 5356 filler wire on mechanical properties of AA2219 aluminium alloy. The following conclusions were made based on their study. There is an increase in the hardness values of weld metal by the addition of scandium. This increase of hardness is predominant in the presence of Magnesium. The addition of small amount of scandium also resulted in a fine grain structure in 2219 aluminum alloy weld metals[12].

Inferior weld strength, reduced ductility of the weld metal and heat effected zone, poor corrosion resistance and crack formation are some key issues in the welding of 6082 aluminium alloy. These issues can be addressed by changing the chemical composition of the filler material. From the previous literatures, it is very clear that magnesium content in the filler wire is an influential parameter. So far no research has been carried out to investigate the effect of changing chemical composition of filler wires on the mechanical properties of welded joints. The objective of the research is to study the effect of adding magnesium to the commercially available ER 4043 filler material on microstructure and mechanical properties of TIG welded AA6082 aluminium alloy. In the present investigation, magnesium is added to silicon-based 4043 filler material at different percentage levels, and this new filler wires are used for TIG welding of 6082 aluminium alloy.

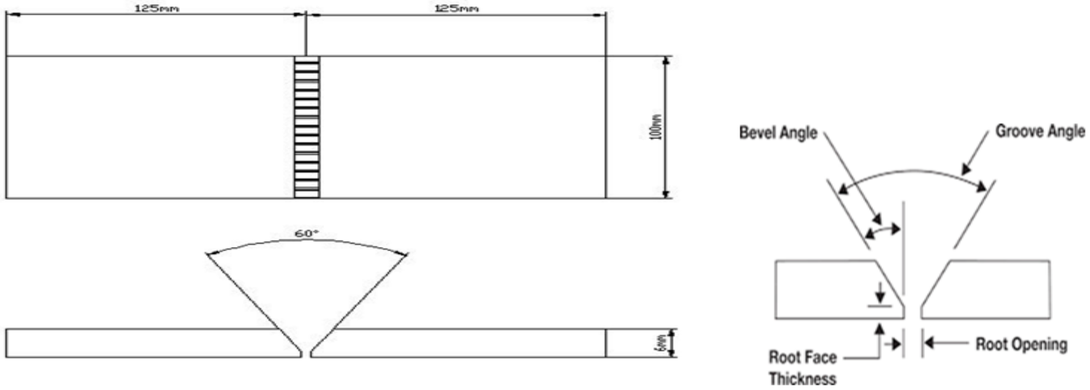
2. EXPERIMENTAL WORK

2.1 Materials and Method

A6082 aluminium plate of 6 mm thick was the material used for this investigation. The chemical composition of the aluminium alloy was obtained by spark optical emission spectrometry. In this, test spark was generated between a metal sample and an electrode by applying electrical energy. The generated spectrum was analyzed for detecting the quantitative and qualitative analyses of the sample. The chemical composition of the base metal and different types of filler material used in this investigation are given in Table 1. Aluminium plates of dimension 125x100x6mm thick were used as the work piece dimensions. The work piece material was machined by using a milling machine to make V groove on the edge. The included angle of the V groove was kept at 60^0 and root face was kept at 2mm. Edge preparations were done with standard groove angle and root gap. The sketch of the work piece with dimensions is given in figure1.

Table 1: Chemical Composition of the Materials

Material	Mg	Si	Fe	Mn	Cr	Cu	Ti	Zn	Sn	V	Be	Others	Al
AA 6082	0.87	0.95	0.15	0.77	0.02	0.02	0.01	0.08	0.01	0.01	----	-----	Balance
ER 4043	0.05	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance
ER 4043+1.5% Mg	1.52	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance
ER 4043+3% Mg	3.03	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance
ER 4043+4.5% Mg	4.56	4.5-6	0.80	0.05	-----	0.30	0.20	0.10	---	---	0.0008	0.05	Balance



Bevel angle	30^0
Groove angle	60^0
Root face thickness	2.0 mm
Root opening	1.5mm

Figure 1: Work Piece Dimensions.

ER 4043 filler wires, with magnesium added at different percentage levels, were used for the welding. New filler wires were made by adding magnesium at varying percentage levels to the commercially available ER 4043 filler wire. First, ER 4043 filler was melted in an electric metal melting furnace and to this molten metal magnesium was added in ribbon form. Care had been taken to prevent the oxidation of magnesium by supplying argon inert gas shielding on the surface of molten metal. This molten material was then poured into a boron silica glass tube of 4mm inner diameter and 200 mm length. After solidification the cast filler wires were taken out by breaking the glass tube. By using this casting process, different filler wires were made with 1.5, 3.0 and 4.5 percentage of magnesium content in the wire. The weight of commercial filler wire ER4043 and the weight of the magnesium ribbon taken for making different filler wires are given in Table 2. The magnesium content in the novel filler wire was confirmed by chemical analysis. The filler wires made by the casting process are shown in the figure 2.

Table 2: Weight of Magnesium

Filler	Weight of 4043 Filler Wire Melted (gram)	Weight of Mg Added(gram)	% Silicon in Filler Wire	% of Magnesium in Filler Wire	Remarks
ER 4043	-----	-----	5	0	Standard filler
ER 4043+1.5%Mg	200	3	5	1.5	New filler
ER 4043+3%Mg	200	6	5	3	New filler
ER 4043+4.5%Mg	200	9	5	4,5	New filler

Figure 2: Magnesium Added Cast Filler Wire

2.2 Selection of Process Variables

The key process variables that influence the mechanical properties of the welded joint were identified. From the investigations done previously, the effect of arc voltage, shielding gas composition and torch angle were found to have less significant role in the mechanical properties of welded joints [13-17]. Therefore, these parameters were not considered in this investigation. Since specially manufactured filler wires were used in this study, manual TIG welding method was used to overcome the compatibility issues of automatic filler wire feeding mechanism. The most appropriate welding speed which will give good bead geometry, good weld soundness and proper penetration was identified from a series of trial runs. Welding speed was maintained at a constant value of 100 mm/min by the hand control of a skilled welder. In this investigation, welding current, chemical composition of the filler wire and shielding gas flow rate were selected as welding parameters.

2.3 Levels of Identified Parameters

Trial welding experiments were conducted to identify proper working range of all the welding parameters under consideration. All the four types of filler wires with varying magnesium content manufactured by casting were used in the trial runs. Different levels of process parameters were considered for the trial experiments. From the trial runs, the maximum and minimum levels of each of the process parameters were determined. The working ranges of the different process parameters thus obtained are given in Table 3. In order to minimize the number of experiment trials in the design of experiments, only three levels of current and three levels of gas flow rate were selected. The maximum percentage of magnesium in the filler wire was restricted to 4.5%, which is near to the range of silicon content in the 4043 filler wire.

Table 3: Levels of the Welding Parameters

Factor	Units	Level 1	Level 2	Level 3	Level4
Current	A	190	210	230	---
Gas flow rate	L/Min	13	14	15	---
Mg Content	%	0	1.5	3.0	4.5

2.4. Design of Experiment

The design of experiment is a systematic procedure used to investigate the effect of various input parameters that have influence on the output of a process [18]. It can also be used to improve the output of a process. Factorial design approach is used for designing the experiments. Factorial design is primarily used for screening the significant factors that influence the response variable in a process. The factorial design is a design of experiment method used for studying the effect of

different input parameters on the output of the process. By this method, it is also possible to analyze the interaction effect of input parameters on the output variable. Factorial designs are subdivided into full factorial design and fractional factorial design. In the present investigation, full factorial design is used for optimization. The factorial matrix design is given in Table 4.

2.5 Experimental Procedure

TIG welding is performed by selecting the values of the process parameters as per the design matrix. Lincoln make TIG welding machine available at Welding Research Institute-BHEL- Trichy was used for this investigation. To remove stains and contamination, the work piece materials were pickled with a solution of NaOH and HNO_3 before welding. In order to remove the oxide film on the surface, the work pieces were cleaned with a buffing wheel and also decreased with acetone. The work pieces were fixed on the welding fixture with steel backing plate and clamped to it to maintain a uniform root gap and alignment, as shown in figure 3. Manual welding was carried out and operation completed in two passes (Figure 4). Thirty-six welded specimens were made as per the process parameters in the design of experiments. Some of the welded specimens are shown in figure 5. Specimens for conducting hardness test were taken from the work piece in the area of sound weld and good weld bead appearance. The specimens were prepared as per ASTM E 92-82 standards. Vickers hardness test was used for measuring the hardness of material. It uses a square-based pyramidal diamond indenter to make indentation on the surface of the test material. A test force is using for some specified time to mark the indentation. The Vickers hardness number is obtained from the lengths of the two diagonals of the projected area of the indentation [19]. Hardness testing of all the specimens was performed by using Vickers hardness testing machine. The results are tabulated in Table 4.

Table 4: Design Matrix - Factorial Design

Std Order	Run Order	Level of Factor			Vickers Micro Hardness at Weld Center(HV)
		Current (A)	Gas Flow Rate (L/Min)	Mg (%)	
8	1	190	14	3.0	76.1
16	2	210	13	1.5	74.2
33	3	230	15	3.0	74.9
7	4	190	13	3.0	73.8
29	5	230	14	1.5	73.2
12	6	190	15	4.5	66.3
22	7	210	13	4.5	68.1
31	8	230	13	3.0	75.2
6	9	190	15	1.5	70.8
13	10	210	13	0.0	67.9
26	11	230	14	0.0	66.7
1	12	190	13	0.0	63.1
19	13	210	13	3.0	78.1
9	14	190	15	3.0	77.3
30	15	230	15	1.5	72.0
34	16	230	13	4.5	64.9
35	17	230	14	4.5	66.2
15	18	210	15	0.0	66.0
3	19	190	15	0.0	63.3
27	20	230	15	0.0	63.4
25	21	230	13	0.0	65.9
2	22	190	14	0.0	65.8
24	23	210	15	4.5	67.7
32	24	230	14	3.0	78.1
5	25	190	14	1.5	76.0
28	26	230	13	1.5	73.1
10	27	190	13	4.5	67.2

11	28	190	14	4.5	67.1
20	29	210	14	3.0	81.0
17	30	210	14	1.5	75.2
36	31	230	15	4.5	64.3
4	32	190	13	1.5	70.1
21	33	210	15	3.0	79.0
14	34	210	14	0.0	67.7
23	35	210	14	4.5	66.2
18	36	210	15	1.5	74.3

Figure 3: TIG Welding Fixture

Figure 4: TIG Welding.

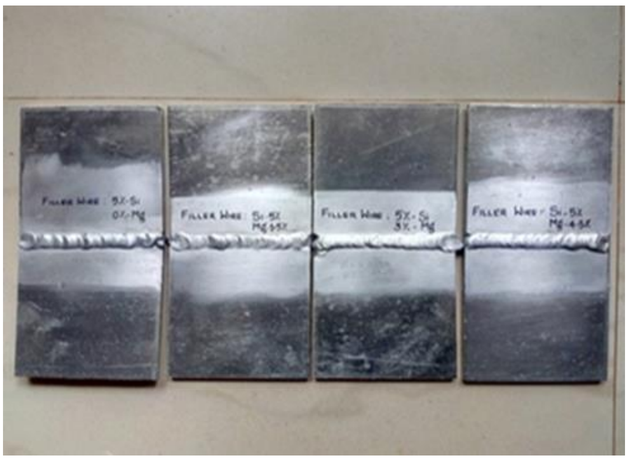


Figure 5: Welded Specimens.

3. ANALYSIS OF VARIANCE-ANOVA

Analysis of variance is a statistical method used to evaluate the differences among group means in a sample observation. It gives a clear picture of the extent to which process parameter affects the response, and the level of significance of each factor under consideration. It can also give information about measurement errors and uncontrolled parameters associated with an experiment. The suitability of the model in experimentation can be checked with ANOVA with the help of F statistics. If the calculated value of F ratio is higher than the tabulated value of F-ratio, then it is confirmed that the developed model is satisfactory for representing the relationship between the response parameter and control factors at a desired level of significance. Analysis of variance was carried out by using Minitab 18 software and the results are shown in Table 5. The higher F value implies that the corresponding term makes a significant contribution to the response. The percentage contribution of different parameters was determined by calculating ratio of sum of squares corresponding to that parameter to the total sum of squares. From the empirical model developed by analysis of variance the optimum current and gas flow rate were calculated by using artificial neural network and genetic algorithm. Four samples were additionally welded by using these optimum current and gas flow rate and also with filler wires of different magnesium content for the determining hardness of the weld metal.

Table 5: Analysis of Variance - Minitab Output

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	23	918.15	39.92	30.10	0.001
LINEAR	7	885.81	126.54	95.42	0.001
CURRENT	2	43.91	21.95	16.55	0.001
% Mg	3	822.35	274.11	206.69	0.001
GAS FLOW.RATE	2	19.54	9.77	7.37	0.008
TWO WAY INTERACTIONS	16	32.34	2.02	1.52	0.233
CURRENT*% Mg	6	11.98	1.99	1.50	0.257
CURRENT* GAS FLOW RATE	4	7.84	1.96	1.48	0.259
% Mg* GAS FLOW RATE	6	12.52	2.08	1.57	0.237
ERROR	12	15.92	1.33		
TOTAL	35	934.06			

S	R^2	R^2 (Adj)	R^2 (Pred)
1.15	98.30%	95.03%	84.67%

The empirical model obtained showing the relationship between the hardness of the weld metal and selected welding parameters is given below:

H V = -587 + 2.880 Current + 10.65 % Mg + 50.3 Gas Flow Rate -1.625 Gas Flow Rate*Gas Flow Rate - 0.0150 Current*% Mg - 0.0250 Current*Gas Flow Rate + 0.144 % Mg*Gas Flow Rate

3.1 Optimization of Process Parameters

The optimum percentage of magnesium in the filler material for obtaining maximum hardness of the welded joint was found out by using Artificial Neural Network (ANN) and genetic algorithm. A fitting function which gives the relationship between hardness and the process parameters under consideration was generated by using ANN. The optimum values of the process parameters for maximum hardness were obtained by solving the fitting function in Genetic Algorithm. The screen shot of the optimization tool which shows the optimum values of the process parameters is shown in the figure 6.

The regression plots for training and validation in genetic algorithm is shown in figure 7. The optimum welding parameters obtained are 214.87A current, 13.58 L/Min gas flow rate and 2.71% magnesium content in the filler wire.

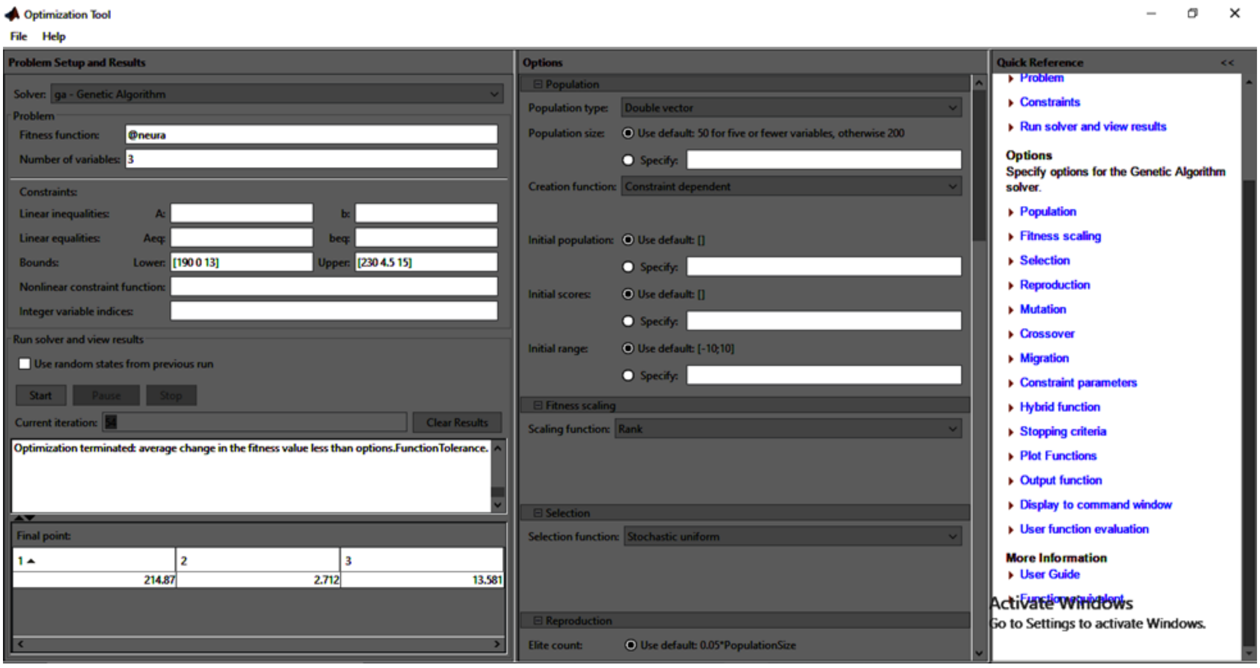


Figure 6: Genetic Algorithm Output

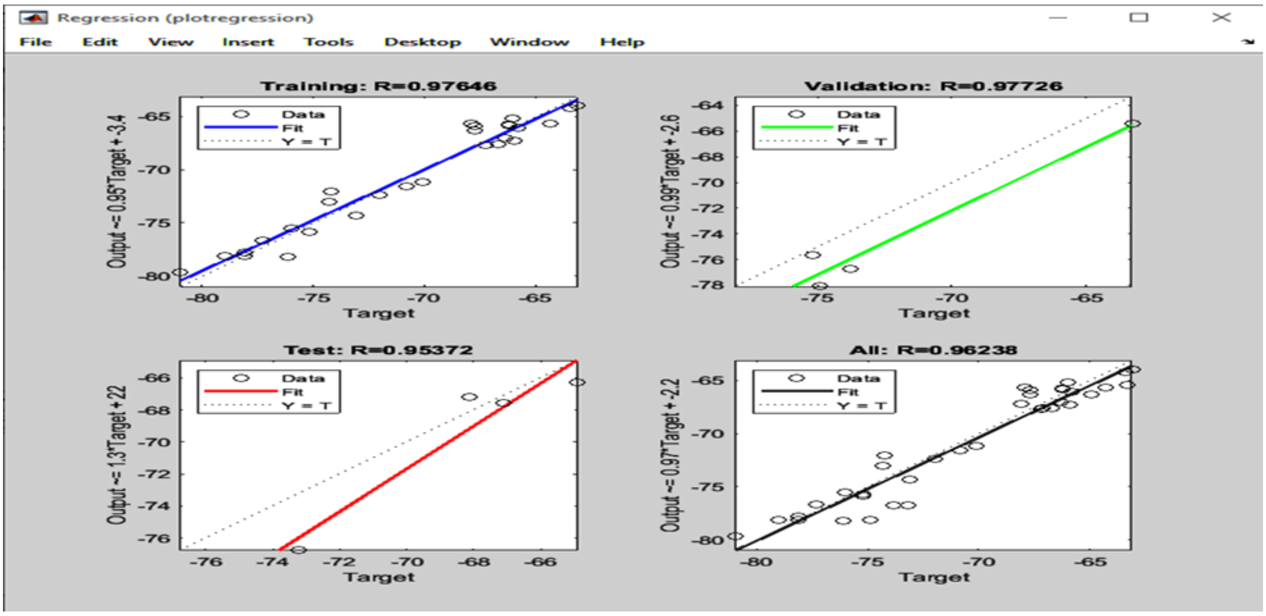


Figure 7: Regression Plot - Genetic Algorithm

4. RESULTS AND DISCUSSIONS

The effect of adding magnesium to the filler wire on the hardness of the weld metal is investigated by using design of experiment method. From the analysis of variance, it is evident that magnesium content in the filler wire has a significant role in the hardness of the welded material. From ANOVA, it is clear that adding magnesium to the ER4043 filler wire considerably improved the hardness of the welded joint. It is noticed that the maximum hardness for the welded joint is

obtained by adding 2.71% of magnesium in the filler wire. From ANOVA, the contribution of each of the parameters is calculated and it is found that magnesium content in the filler wire is the most significant parameter which influenced the hardness of the joint with 88% contribution. The p value of less than 0.05 strongly supports the rejection of the null hypothesis. The percentage of contribution for current is found to be 5%. The contribution of current is comparatively low here because the range of value of current is selected in such a way that it would result in a sound weld. Current value below 190 A is not considered in this experiment because it will result in lack of fusion due to insufficient heat input. Similarly, current value above 230 A is not considered either, because it will result in the burning of base metal due to excess heat input. So, both low and high values of current will result in reduced strength of the joint. Gas flow rate is not a significant parameter and the contribution of the same is limited to 2%. The two-way interaction effect of current and gas flow rate, gas flow rate and magnesium content in the filler wire, current and magnesium content in the filler wire have negligibly small significance with less than 2% contribution. The details are given in Table 6.

Table 6: Contribution of Process Parameters

Sl. No	Parameter	Type of Interaction of Parameters	Percentage of Contribution
1	Magnesium content in the filler wire	Linear	88
2	Current	Linear	5
3	Gas flow rate	Linear	2.0
4	Current*Gas flow rate	Two way	1.2
5	Current*% Mg	Two way	0.8
6	Gas flow rate*% Mg	Two way	1.3
7	Error		1.7

4.1 Distribution of Hardness

The variation in hardness value across the weld cross section was obtained by measuring hardness value at different sections on the left and right side of the weld bead. The hardness was measured in fusion zone, heat effected zone and base metal at specified points as shown in figure 8. Four samples were welded again with optimum values of current and gas flow rate. Samples were polished to measure Vickers micro-hardness. The weld center was taken as the reference point and marked as 0 mm. The hardness value at different distance from the weld center on both sides of the weld was obtained so that variation of hardness value in the weld zone, heat affected zone and base material could be studied. The experiments were repeated for samples welded with filler wires of different magnesium content. The results are tabulated in Table 7. The highest hardness value obtained at fusion zone is 74.2 HV for the filler wire with 3% magnesium. In the heat affected zone, hardness value was decreasing for all the samples welded with different filler wires. The hardness was measured from the weld bead center to the heat affected zone with an approximate separation of 2mm mm between measurements. Buehler Indentamet 1100 series hardness tester is used with a test load of 5 kg for 15 seconds. Vickers micro-hardness measurements were taken for all the samples in the as-welded condition.

The hardness distribution of specimen welded with filler wire with no magnesium content is shown in figure 9. In this case, the maximum value of hardness obtained in weld metal is 64HV and when moving towards the heat affected zone, hardness decreases to 58.1HV. The reduction in hardness is due to the deterioration of elements initially present in the base metal and due to the formation of precipitates in the over aged metal portion [20].

For specimens welded with 1.5% of magnesium content in the filler wire, there is an increase in the hardness value of the weld metal to 66.3 HV (Figure10). Like this, for specimen welded with 3% magnesium content in the filler wire, the hardness value of the weld metal obtained is maximum with value of 74.3 HV (Figure 11). Further addition of magnesium in the filler wire to 4.5%, reduces the hardness value of the weld metal to 69.8HV (Figure 12). This decrease in hardness is may be due to the excess formation of bigger size β Mg_2Si intermetallic phase [21-22].

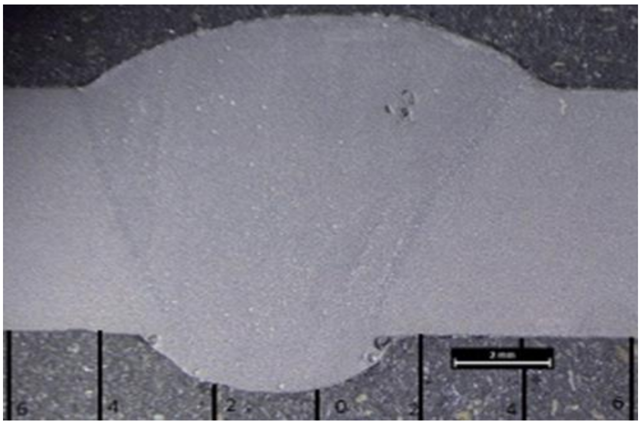


Figure 8: Micro hardness (HV) Measurement Positions

Table 7: Vickers Hardness at different Weld Sections

		Hardness value (HV)												
Filler	ER 4043	94.9	94.6	68.0	58.1	63.2	63.8	64.0	63.3	63.2	58.2	68.0	94.8	95.2
	ER 4043+1.5% Mg	95.3	94.7	68.1	60.1	66.5	66.4	66.3	66.5	66.3	60.2	67.2	94.5	95.1
	ER 4043+3.0% Mg	95.1	94.5	64.5	63.2	73.1	74.2	74.3	74.4	73.2	62.2	64.8	93.8	95.4
	ER 4043+4.5% Mg	95.2	94.3	63.3	60.1	68.5	69.1	69.8	69.7	68.6	60.2	63.0	94.2	95.1
		-12	**-10**	**-8**	**-6**	**-4**	**-2**	**0**	**2**	**4**	**6**	**8**	**10**	**12**
		Distance from weld center in mm												

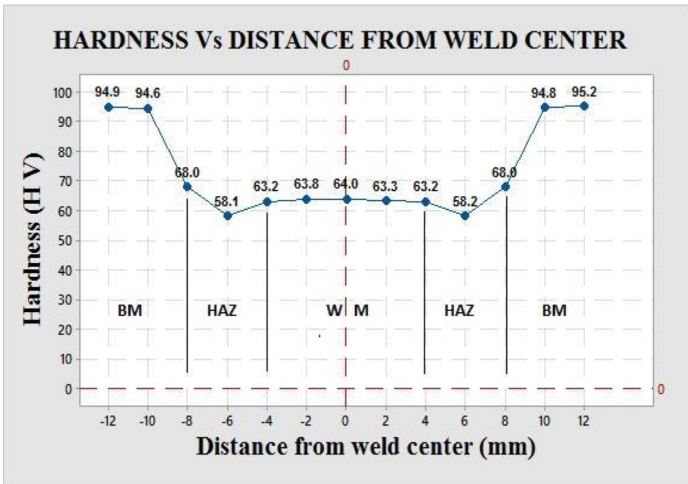


Figure 9: Hardness Distribution-0% Mg in the Filler Wire.

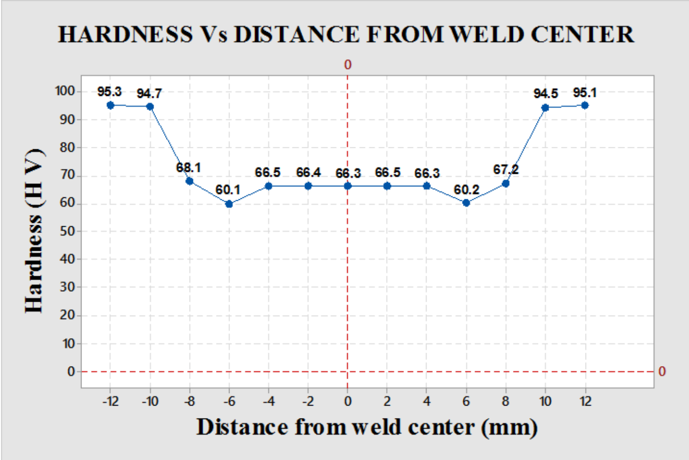


Figure 10: Hardness Distribution-1.5% Mg-Added Filler Wire.

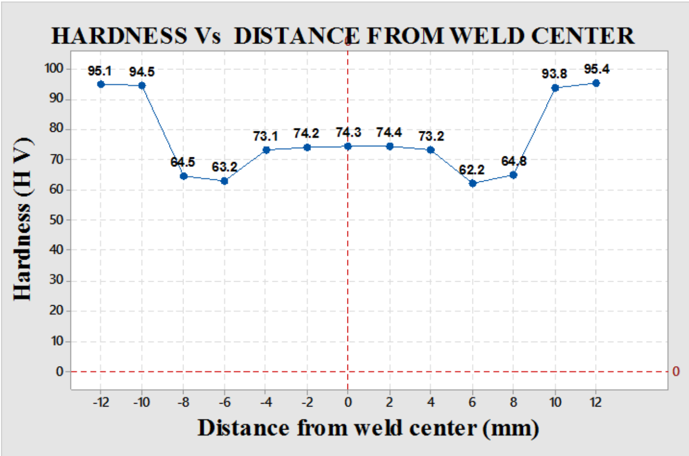


Figure 11: Hardness Distribution 3% Mg-Added Filler Wire.

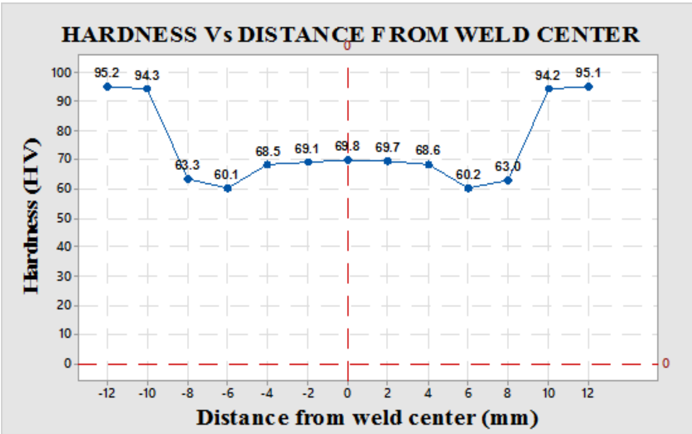


Figure 12: Hardness Distribution- 4.5% Mg-Added Filler Wire.

4.2 Microstructure and Intermetallic Phase

To study the improvement obtained in the hardness of the weld metal, the microstructural examinations were carried out by using scanning electron microscope and optical microscope. All specimens welded with filler wires of different magnesium content were included in SEM examination to compare the results. Specimens were taken from the work piece using abrasive cut-off wheels. Grinding and polishing were carried out as per the standard metallographic procedures. For

revealing more microstructural features, the specimens were etched using Kellers reagent (1ml HF, 1.5ml HCL, 2.5ml HNO3 and 95ml H_2O). The microstructures of the weld metal were captured with the help of image-analyzing software coupled with an optical microscope at a magnification of 400X. The microstructure of the specimens welded with filler wires of different magnesium content are given in figure 13 to 16. The microstructure of the joint welded with ER 4043 i.e. wire containing no magnesium content resulting in a coarse grain structure is shown in figure 13. The average hardness observed is low in this case. The coarse grain structure is responsible for the comparatively lower hardness of the weld metal. Small traces Mg_2Si can be seen as dark spots in the microstructure of the metal welded with 1.5% of magnesium in the filler wire (Figure 14). The presence of Mg_2Si occupied in the inter granular space is more visible in the microstructure of the welded joint made with filler wire of 3% of magnesium content as shown in figure 15. An addition of magnesium by 4.5% further intensifies the formation of Mg_2Si in inter granular space (Figure 16). Up to a certain range the presence of Mg_2Si is useful for grain refinement, but any excess quantity of Mg_2Si weakens the strength and hardness [23].

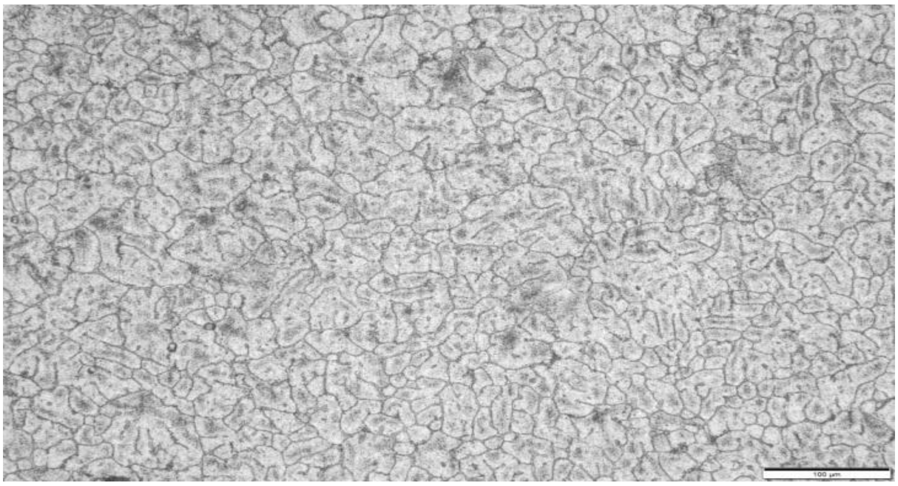


Figure 13: Microstructure of Weld Metal with 0% Mg in the Filler Wire - As Welded Condition [23]

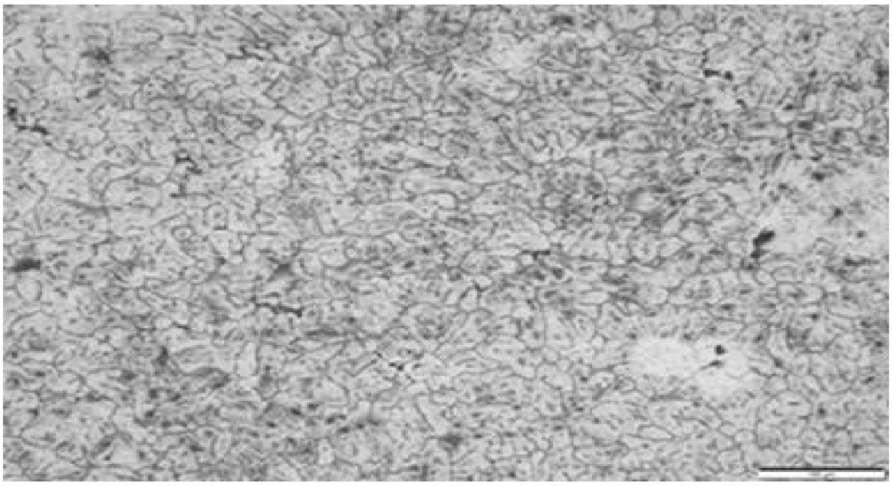


Figure 14: Microstructure of Weld Metal with 1.5 % Mg-Added Filler Wire - As Welded Condition [23]

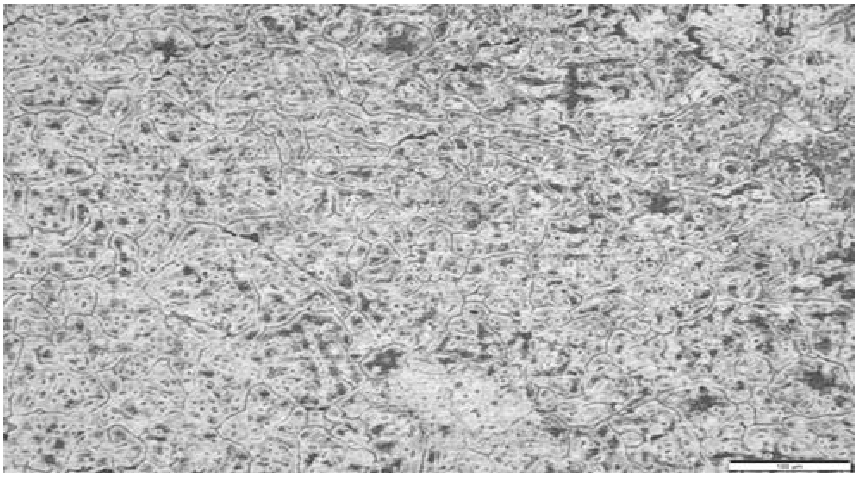


Figure 15: Microstructure of Weld Metal with 3 % Mg-Added Filler Wire - As Welded Condition[23]

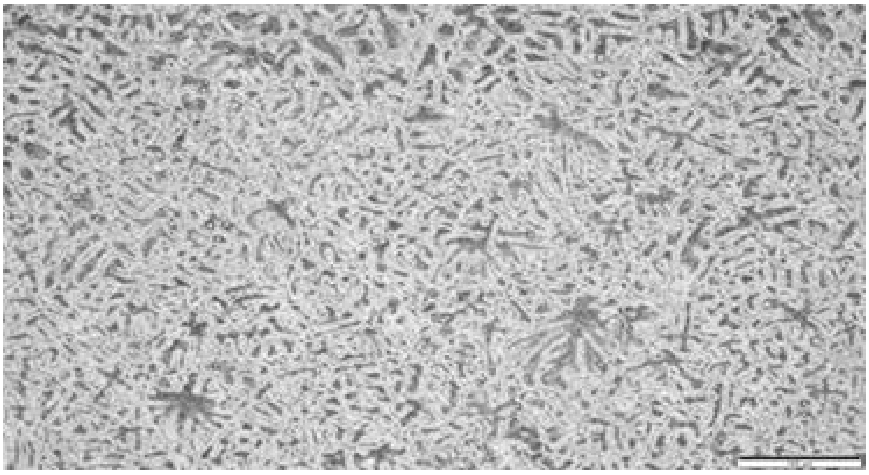


Figure 16: Microstructure of Weld Metal with 4.5% Mg-Added Filler Wire -As Welded Condition[23]

SEM microstructures of the specimen welded with ER 4043+ 3% Mg are shown in figure 17. SEM microstructure study clearly shows the presence of Mg_2Si as dark spots. The formation of intermetallic particles of Mg_2Si along the grain boundary of the alloy is responsible for the improvement in the hardness of the weld metal. The composition of the weld metal was studied with the help of Energy Dispersive X-ray Analysis (EDXA) incorporated with scanning electron microscope. The EDXA spectrum of the specimen welded with ER 4043+ 3% Mg content is shown in figure 18. The EDXA confirms the presence of magnesium and silicon in the weld metal. SEM microstructures of the specimen welded with ER 4043+ 0% Mg is shown in figure 19. The EDXA of the same specimen is shown in figure 20, the presence of silicon is very clear in the EDXA spectrum but no magnesium is found on the same.

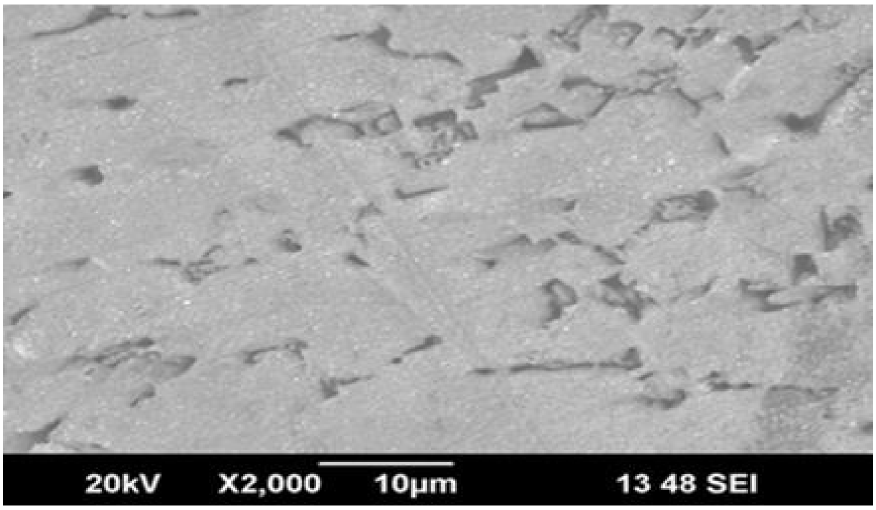


Figure 17: SEM Image of Weld Metal with 3 % Mg Added Filler Wire [23]

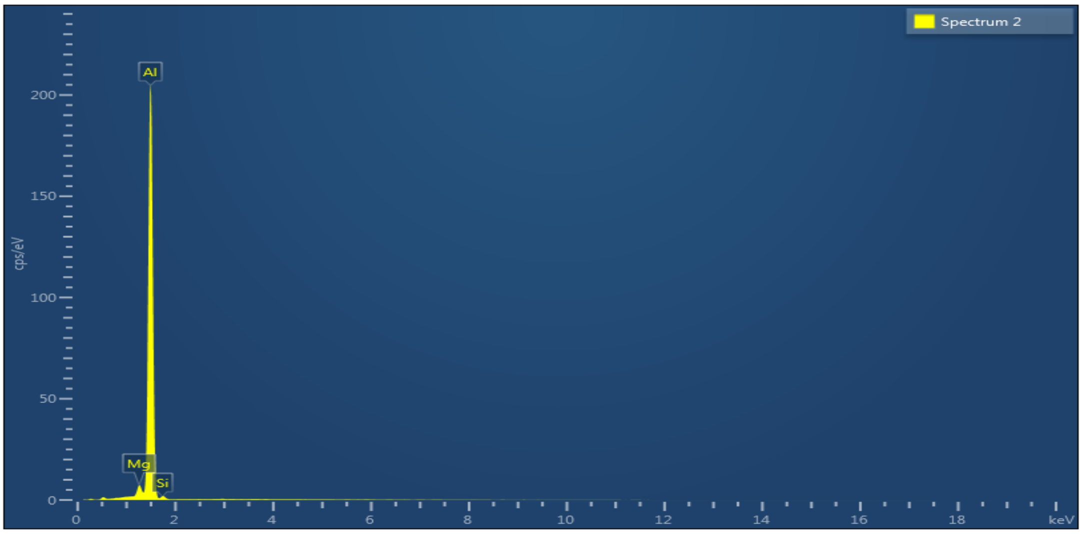


Figure 18: EDXA Spectra of Weld Metal with 3 % Mg Added Filler Wire [23]

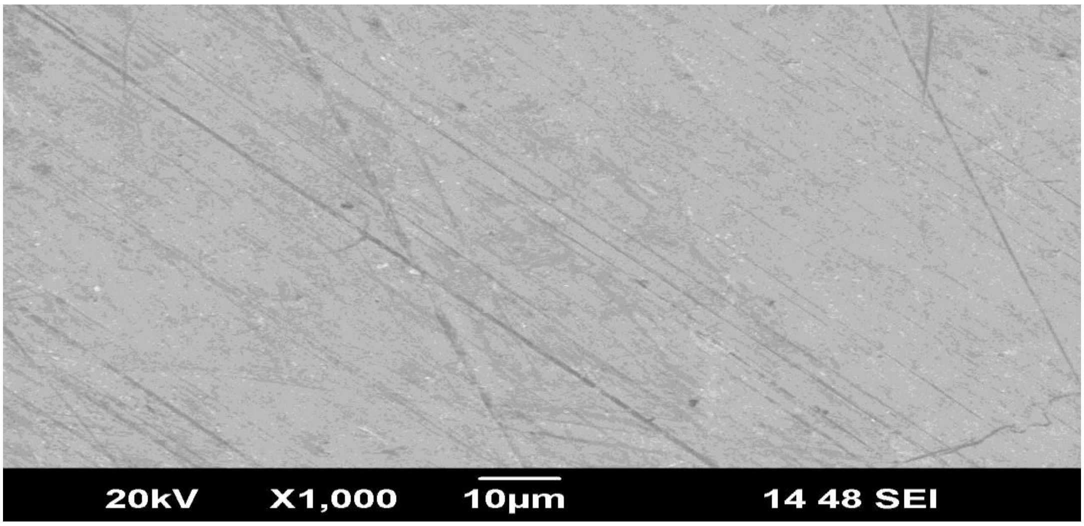


Figure 19: SEM Image of Weld Metal with 0 % Mg in the Filler Wire [23]

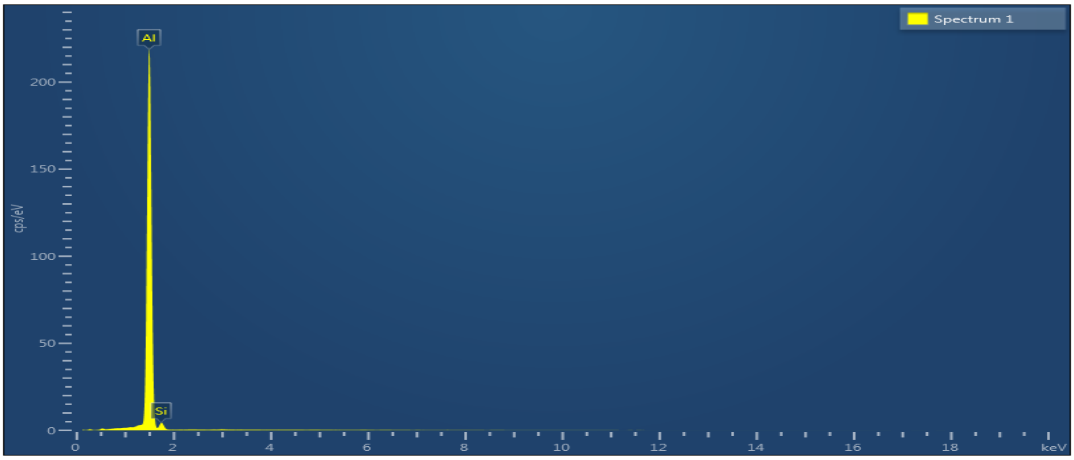
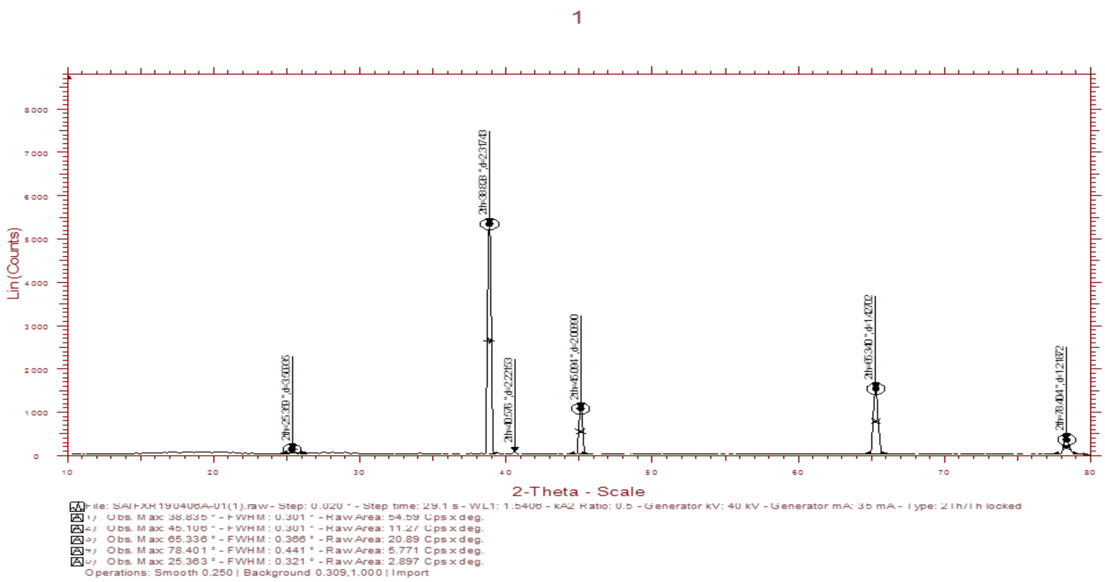


Figure 20: EDXA spectra of Weld Metal with 0 % Mg in the Filler Wire [23]

The X-Ray diffraction analysis was performed to identify the composition of intermetallic compounds in the weld metal. The XRD spectra confirmed the presence of following intermetallic phases in the weld metal: Al_5FeSi, $Al_{15}(FeMn)_3Si$, Al_9Mn_3Si, $Al_{12}Fe_3Si$ and Mg_2Si (Figure 21). These intermetallic phases have various shapes of particles such as needle-like, plate-like, polygonal and "Chinese script". In the aluminium 6000 group of alloys, the intermetallic phases formed during solidification imparts the strength to these alloys [24]. From previous investigations and literature, it has been found that the formation of β″(Mg2Si) phase and precipitation of intermetallic phases containing Si, Fe and Mn play a significant role in the superior mechanical properties of these alloys [25,26]. The amount of strengthening depends on the extent of β″ precipitation during the solidification, and with an increase of Mg content in the filler wire, the β″(Mg2Si) precipitation increases [27,28]. In terms of size and distribution, it can be located at the grain boundaries and it may form a dendritic network structure. The presence of various intermetallic phases can improve the strength of the fusion zone by a mechanism called precipitation strengthening effect [29, 30]. The presence of Mg_2Si can improve micro-hardness, and hard intermetallic compounds can improve the mechanical properties of the fusion zone [31-33].



1.$Al_{15}(FeMn)_3Si$ 2.Al_9Mn_3Si 3.Mg_2Si 4.Al_5FeSi 5. $Al_{12}Fe_3Si$

Figure 21: XRD Spectra of weld metal with 3 % Mg Added Filler Wire [23]

Variation in the hardness of the welded joint with current and amount of magnesium in the filler wire is shown in the contour plot (Figure 22). From this plot, it is evident that magnesium content around 3% can substantially improve the hardness of the joint. The main effect plots showing variation in hardness and the key parameters is shown in the figure 23. It is clear that by adding magnesium in the 4043filler wire hardness of the joint can be improved. The variation of the hardness of the weld metal with magnesium content in the filler fire, current and gas flow rate are given in figure 24-26. The mean hardness obtained is maximum at a current of 210 A, and the value of mean hardness at this value of current is 72.2 HV, which is shown in figure 24. Similarly the mean hardness obtained is maximum at 3% magnesium content in the filler wire. The value of hardness at this percentage of magnesium content is 77.1 HV (Figure 25). The mean hardness obtained is maximum at a gas flow rate of 14 liters per minute as shown in figure 26.

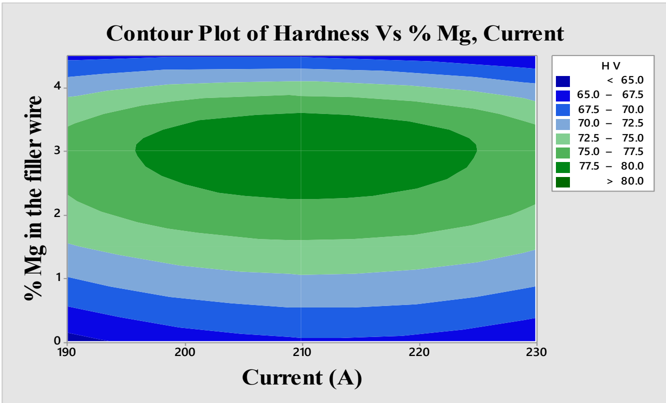


Figure 22: Contour Plot

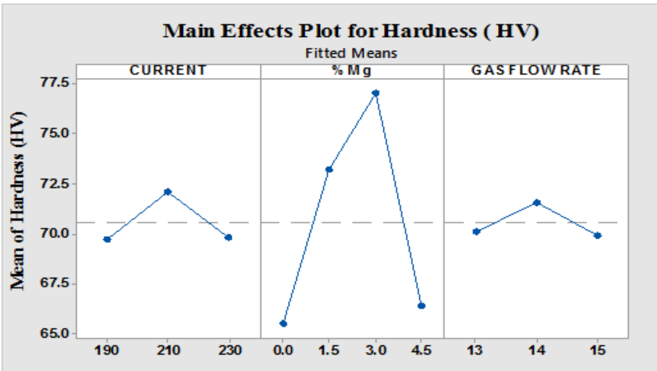


Figure 23: Main Effects Plot

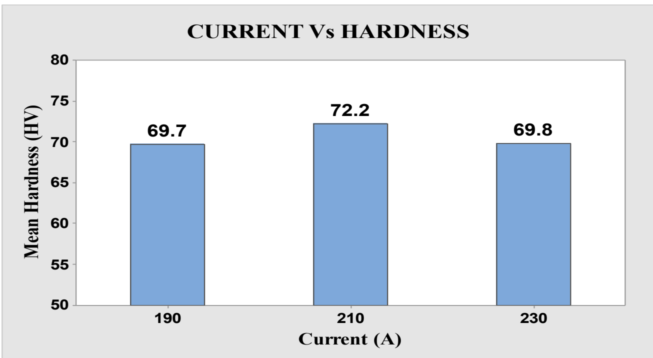


Figure 24: Current Vs Hardness

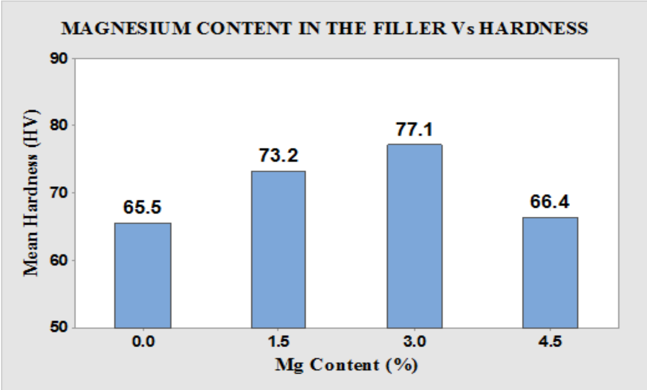


Figure 25: Mg Content Vs Hardness

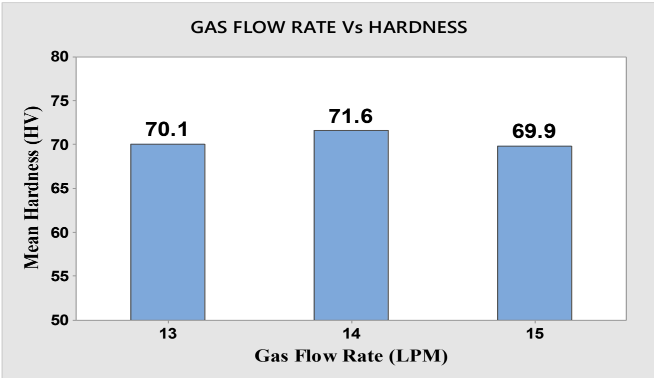


Figure 26: Gas Flow Rate Vs Hardness

4.3 Confirmation Test

For comparing the hardness as predicted by the model with the experimental value, a confirmation test was conducted by selecting the optimum welding parameters. The optimum welding parameters obtained were 210.93. A current, 13.707 L/Min gas flow rate and 2.71% magnesium content in the filler wire. Three samples were welded by selecting the above parameters and hardness test was carried out for these specimens. The results of the confirmation test are shown in table 8. Excellent agreement between the hardness predicted by the model and the experimental value validates the hypothesis.

Table 8:Confirmation Test

Optimum Process Parameters			Hardness Predicted by Model (H V)	Hardness Experimental (HV)
Current(A)	Gas Flow Rate L/Min	% Mg		
214.87	13.58	2.71	78.58	78.60
				77.90
				78.20

5. CONCLUSIONS

The new filler wire developed with both magnesium and silicon content is very effective for the welding of 6082 aluminium alloys. From the present investigation, it is found that the addition of magnesium up to 2.71% by weight to commercially available ER4043 filler wire can substantially improve the mechanical properties of the welded joint. The improvement in the hardness is due to the formation of some new intermetallic phase in the weld metal, mainly magnesium silicide. From the investigation, it is also found that filler wire chemical composition plays a significant role in the hardness

of the weld metal. Further research would be useful for making improvements in this new filler wire developed, so that it will provide better mechanical properties for the welded joint.

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